Bio-optical drifters - Scales of variability of chlorophyll and fluorescence

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ABSTRACT

Both the California Current System and the Antarctic Polar Front are characterized by mesoscale variability and meandering jets. These meanders lead to regions of strong vertical motion, on the order of several tens of meters per day. To study physical and biological scales of variability in these two systems, near-surface drifters were released in these two environments; twenty-six in the California Current and five in the Polar Front. Each drifter was equipped with a spectroradiometer to measure upwelled radiance at the SeaWiFS wavelengths as well as at 683 nm. A temperature system was also included. Data were relayed to shore via satellite. These data were converted into biological quantities, including chlorophyll and an apparent quantum yield of fluorescence. Decorrelation time scales were calculated and compared with corresponding statistics of the physical environment. Time scales for all variables increased as the drifters moved from nearshore to offshore. The scales associated with temperature and chlorophyll were similar nearshore, but increased more rapidly offshore for temperature. This suggests that the processes regulating the distribution of temperature and chlorophyll are similar in the nearshore region and significantly differ offshore.

Keywords: California Current, upwelling, time scales, phytoplankton, drifters, chlorophyll, fluorescence

INTRODUCTION

Over the past decade, developments in smaller and less expensive instrumentation have allowed oceanographers to collect data sets at time and space scales that are difficult to observe from conventional platforms.[1] For example, time series from a fixed point mooring are a combination of both temporal changes and spatial changes as new water masses are swept past the mooring. Free-drifting buoys that can be drogued to follow upper ocean circulation help separate temporal variations in a water mass from those that occur spatially. Bio-optical drifters deployed in the California Current were initially used to examine physical and biological processes within a specific physical feature.[2,3] The advent of lower cost sensors as well as the use of satellite data relay now allows the deployment of large numbers of drifters to conduct systematic studies of the statistical properties of the upper ocean bio-optical field. In this paper, we restrict our discussion to results of drifter studies in the California Current although some bio-optical drifters were also deployed in the Southern Ocean. Our analyses followed two paths. First, we calculated large-scale statistics of the biological and physical fields. Second, we analyzed the impact of specific physical features on upper ocean biology.

METHODS

The standard World Ocean Circulation Experiment (WOCE) surface drifters have been modified by METOCEAN Data Systems to include a Satlantic spectroradiometer (OCR-100) in the bottom of the surface float. This sensor measures upwelled radiance at 412, 443, 490, 510, 555, 670, and 683 nm. The surface float also includes pressure and temperature sensors. A Satlantic narrow band irradiance sensor (ED-100), centered at 490 nm, is mounted in the top of the surface float. A 40 m long drogue is attached below the surface float such that the drifter responds primarily to currents at 15 m depth. Data are averaged over 60 minutes and then transmitted. If a NOAA polar-orbiting satellite is in range, then the message is relayed to shore. Otherwise the message is updated the next hour and the new message transmitted. On average, approximately eight messages were received per day in the California Current and fifteen in the Southern Ocean. The data set also includes "housekeeping" information from the drifter such as battery voltage, number of samples, average time that the surface float was submerged, etc.

Twenty-six drifters were released over a three-year period in the California Current. Three drifters failed soon after deployment (presumably due to high seas); the remainder had an average lifetime of six months with the maximum being nearly ten months. Figure 1 shows all of the drifter tracks collected between 1993 and 1995. Most of the drifters were deployed along a line at 39.5°N between 125° and 128°W. As expected, the general trend is for the drifters to move south and west with the prevailing summertime currents (when most of the drifters were deployed). To date, only five drifters have been released in the Southern Ocean: two in Drake Passage and three in the Polar Front at 170°W. These last three drifters are equipped with a Global Positioning System (GPS) transmitter to provide more accurate location information.

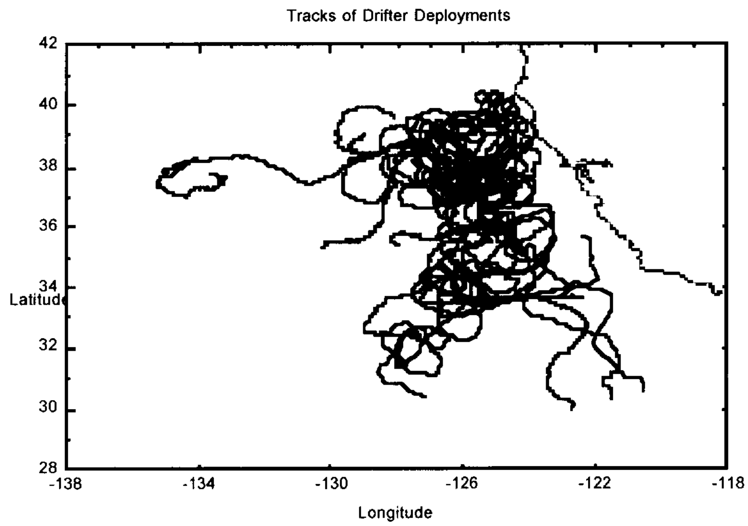

Figure 1. Composite view of drifter deployments in the California Current System in 1993-1994.

Once the data are received, several screening tests are applied to eliminate low quality data points. Occasionally bits are dropped from the Service Argos transmissions, resulting in unrealistic values in many of the drifter variables such as battery voltage, downwelling irradiance, etc. Argos data files also include the position of the drifter. Sometimes these positions are either missing or are obviously in error (sudden, large jumps in position, etc.) The Argos files also include the number of messages received during a given transmission from the drifter. If this number is small, then the probability of erroneous or corrupted data increases. We also screen for bio-fouling (through examination of the level and variability of the 683/555 radiance ratio) and test faulty bio-optical measurements through examination of band ratios. However, the largest amounts of data removed through screening occur when we eliminate those records that were obtained when the absolute solar angle (elevation) is less than 20°. This constrains the study data set to observations collected with a few hours of local solar noon.

After screening, chlorophyll is calculated using the following equation:

$$chl = 0.56353 * \left(\frac{L_u 443}{L_u 555} \right)^{-0.595} \tag{1}$$

where L_u is upwelling radiance at a specific wavelength. This form is derived from earlier bio-optical models,[4] and the coefficients are based on comparisons with chlorophyll samples collected near one of the drifters in 1994.

Once the data files were cleaned and the various derived quantities were calculated, we then estimated decorrelation scales from the drifter data set. We calculated a "daily average" for the variables of interest: SST, chlorophyll, fluorescence/chlorophyll, and drifter speed. Some of the data records were too short or too gappy for further statistical analyses. However, the majority of the drifters were nearly complete with only occasional missing data points. These gaps were filled using linear interpolation between adjacent days. A linear trend was removed from each time series, and the autocorrelation function was calculated. The decorrelation scale was estimated as the point at which this function first became insignificantly different from zero. Figure 2 shows a typical pair of autocorrelation functions for SST and chlorophyll from one drifter in the California Current. Cross-correlation functions were calculated in a similar manner between detrended time series of SST and chlorophyll.

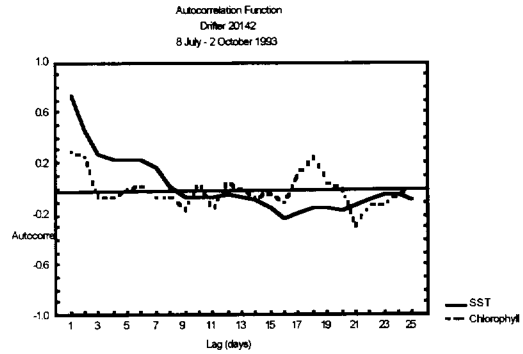

Figure 2. Autocorrelation functions of SST and chlorophyll from drifter 20142. The decorrelation scale is approximately 6.5 days for SST and 2.5 days for chlorophyll.

RESULTS AND DISCUSSION

The average length of the bio-optical time series was 73 days before fouling became evident, although some drifters lasted well over 90 days before there was any evidence in the bio-optical signals that fouling had occurred. For these long time series, it was possible to divide the record into two parts, each one covering a different season. As part of our analysis, we also calculated the average distance from the coast for each drifter.

The average decorrelation time scale was longest for SST at 6.3 days. The decorrelation scale for chlorophyll was 3.7 days, 2.3 days for fluorescence/chlorophyll, and 3.3 days for drifter speed. These results are within the range for the same region off northern California from a study using time series of satellite imagery of chlorophyll and SST.[5] In that study, it was found that the time scales were between one and seven days, depending on length scale.

Figure 3 shows the decorrelation scale for SST, chlorophyll, fluorescence/chlorophyll, and drifter speed as a function of average offshore distance of the drifter. We have divided the distance offshore into three categories: <200 km (nearshore), >200 km but less than 400 km (transition), and > 400km (offshore). There is a general trend for SST and chlorophyll scales to increase as one moves offshore, but this is by no means consistent. However, the more interesting result is that the time scales associated with SST and chlorophyll are relatively similar in the nearshore and diverge as one moves offshore. This suggests that the processes governing SST and chlorophyll are similar in the nearshore region whereas they are controlled by different processes offshore. This is in contrast to earlier results [5] where no significant differences could be detected between the SST and chlorophyll fields. Coastal upwelling should control both SST and chlorophyll in the nearshore, whereas different physical processes or perhaps changes in the biological community lead to different statistical properties of the fields offshore. Another feature of Fig. 3 is that fluorescence/chlorophyll shows more variability nearshore (shorter time scales) whereas it is nearly equal to the chlorophyll time scale offshore. Rapid changes in fluorescence relative to chlorophyll concentration are indicative of variability in the distribution of energy in the photochemical apparatus of the phytoplankton. This observation suggests that in the nearshore region, the time scales of physiological adaptation are significantly shorter than the time scales of changes in phytoplankton biomass.

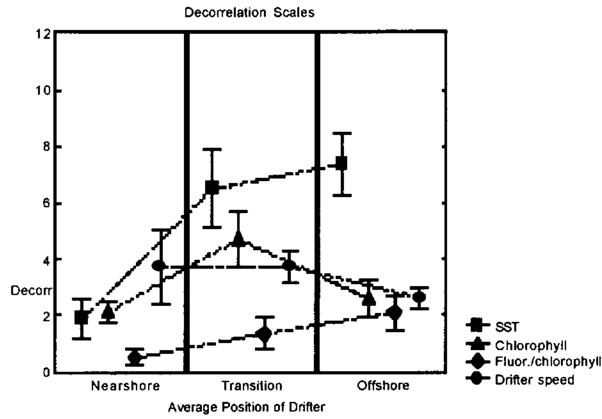

Figure 3. Average decorrelation scales for SST, chlorophyll, fluorescence per unit chlorophyll, and drifter speed as a function of distance offshore. The boxes represent ±1 standard deviation and the whiskers represent ±1 standard error.

Figure 4 shows the track and cross-correlation function for drifter 22622. The drifter made nearly two complete circuits around a large anticyclonic eddy. Note that changes in SST led changes in chlorophyll by one day. Figure 5 shows the same information for drifter 20139 which made two circuits around a much smaller, cyclonic eddy. Although it is not possible to draw robust conclusions from results from two eddies, it is worth noting that the negative correlation (at near zero lag) is much larger in the anticyclonic eddy than in the cyclonic eddy, whereas the cyclonic eddy has large, negative lobes at ±12 days. The time scale of the positive correlations (twelve days for 22622 and six days for 20139) corresponds to the travel time around the eddy (cold water, high chlorophyll on the south side of the eddy and warm water, low chlorophyll on the north). Earlier evidence of a lag between SST and chlorophyll was found in only one region off northern California.[5] It was inferred that this region was near an upwelling center, and that the lag was the result of the delay in biological processes responding to high nutrients in the surface water. In comparison, many of the drifter deployments revealed that changes in SST led changes in chlorophyll by roughly 1-2 days. However, most of the drifters were released in active upwelling regions, and we suspect that the satellite imagery [5] was simply not adequate to evaluate these small time scale patterns.

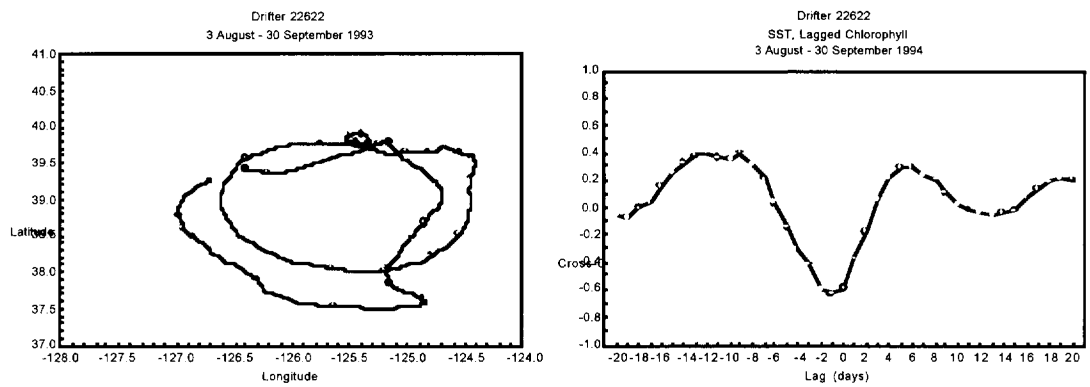

Figure 4. (Left) Track of drifter 22622. (Right) Cross-correlation function of SST and chlorophyll. Negative lags indicate that SST leads chlorophyll.

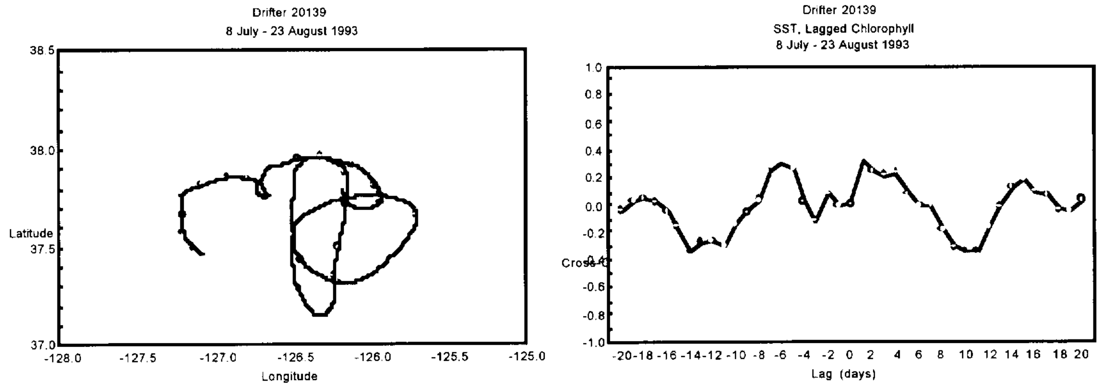

Figure 5. (Left) Track of drifter 20139. (Right) Cross-correlation function for SST and chlorophyll.

Although the optical sensors are calibrated by Satlantic, there are few opportunities to compare readings between sensors in the field unless two or more drifters are found simultaneously sampling the same water mass. Drifter 20140 (not shown) also traversed the same eddy as 22622 (Fig. 4) several days later. Drifters 20140 and 22622 were deployed at 39°33'N, 124°55'W and 39°25', 126°27'W respectively. Although these drifters were released approximately 130 km apart, they followed the same circulation path over a period of 50 days with an average lag time of 18 hours and average distance of 62 km between drifters (Fig. 6, top).

When comparing the temperature records between sensors mounted in these two drifters we observe that both instrument packages appear to be sampling different water masses over the first 30 days (Fig. 6, middle). However, following day 245, the temperature records display strong similarities in the magnitude and trend of the readings, suggesting that both drifters are located in the same water mass. It is also during this period that the distance between both drifters is reduced to an average of 18 km (Fig. 6, top). Furthermore, estimates of algal pigment concentration (chlorophyll a + phaeopigments) also display strong similarities during this period. This observation suggests that, at least in this particular case, the principal physical and biological processes controlling phytoplankton biomass over temporal scales of days appear to be acting over large spatial scales (1-100 km).

Similar trends over the same time period are observed when normalizing the upwelling irradiance at 683 nm (L_u683) and 670 nm (L_u670) to the downwelling radiance measured at 490 nm (E_d490). However, because the absolute value of these measurements differs by a factor of 1.7 between drifters, it is not possible to convert our records into absolute fluorescence quantum efficiency of chlorophyll a. Nevertheless, it is still possible to compare the variance in algal pigment concentration to the variance in relative chlorophyll natural fluorescence. Multiple regression analyses, using model II geometric linear regressions, suggests that the variance in chlorophyll fluorescence is correlated with changes in chlorophyll concentration. However, the correlation coefficient of the regression low ($r= 0.45$, $p < 0.05$) suggesting that the variance in chlorophyll concentration and E_d490 contribute only partially to the variability in absolute chlorophyll natural fluorescence in these water masses.

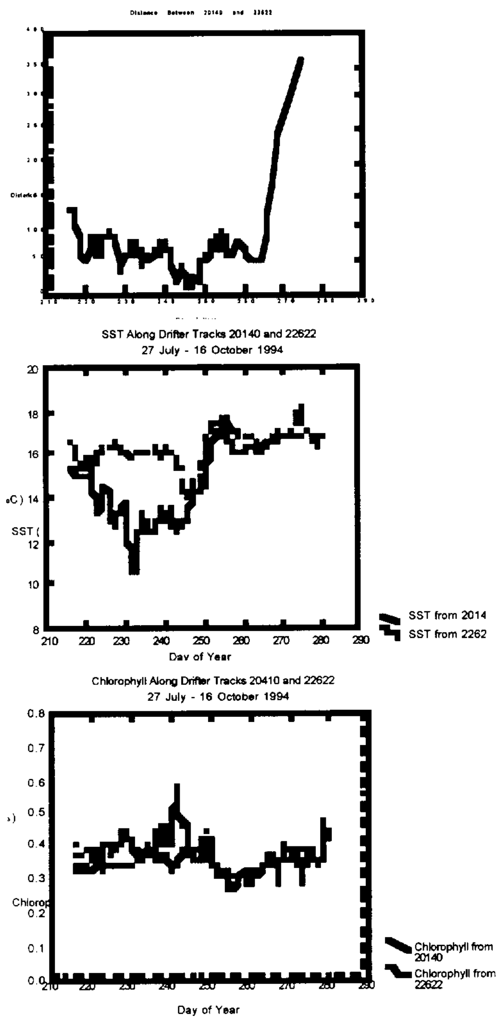

Figure 6. (Top) Distance between drifters 20140 and 22622. (Middle) SST from drifters 20140 and 22622. (Bottom) Same except for chlorophyll.

CONCLUSIONS

Time scales of SST, chlorophyll, and fluorescence/chlorophyll increase as one moves offshore. This is to be expected, given the higher levels of mesoscale variability near the coast.[5] Complex interactions of local wind forcing and ocean circulation should result in intense heterogeneity of vertical motions in the upper ocean, thus affecting SST and nutrient availability, which in turn will affect phytoplankton abundance. This leads to a separation in the statistics of the two data sets, with SST having in general longer time scales than chlorophyll. Although coastal upwelling and presumably rapidly growing phytoplankton dominate the nearshore environment,[6] both biological and physical processes in the offshore environment may be quite different. Historical evidence suggests that the offshore phytoplankton community is dominated by small, slow-growing forms [6] which may lead to a decoupling between the physical processes governing SST and those governing chlorophyll. Given the time scales of phytoplankton growth, we expect to see a lag between changes in the physical environment and the biological response. As most of the drifters covered the summer season, we cannot determine if there is any seasonal modulation in these patterns. Of note is that the decorrelation scales are relatively small, implying that these mesoscale processes will continue to be difficult to resolve with conventional ship sampling.

These interpretations can be further complicated by temporal and spatial changes in the bio-optical models themselves.[3] That is, changes in fluorescence efficiency, particulate backscattering, chlorophyll package effect, etc., will be manifested as changes in chlorophyll abundance and other derived properties. We expect that such changes will act to decrease the decorrelation scales, so that the estimates provided here are likely to be an upper bound on these scales.

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REFERENCES

1. T.D. Dickey, "The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean and their applications," *Rev. Geophys.* **29** (3), 383-413 (1991).

2. M.R. Abbott, K.H. Brink, C.R. Booth, D. Blasco, L.A. Codispoti, P.P. Niiler, and S.R. Ramp, "Observations of phytoplankton and nutrients from a Lagrangian drifter off northern California," *J. Geophys. Res.* **95** (6), 9393-9409 (1990).

3. M.R. Abbott, K.H. Brink, C.R. Booth, D. Blasco, M.S. Swenson, C.O. Davis, and L.A. Codispoti, "Scales of variability of bio-optical properties as observed from near-surface drifters," *J. Geophys. Res.* **100** (7), 13,345-13,367 (1995).

4. D.K. Clark, "Phytoplankton pigment algorithms for the Nimbus-7 CZCS," *Oceanography from Space*, J.F.R. Gower (ed.), 227-238, Plenum Press, New York, 1981.

5. K.L. Denman and M.R. Abbott, "Time scales of pattern evolution from cross-spectrum analysis of advanced very high resolution radiometer and coastal zone color scanner imagery," *J. Geophys. Res.* **99** (4), 7433-7442 (1994).

6. R. Hood, M.R. Abbott, P.M. Kosro, and A.E. Huyer, "Relationships between physical structure and biological pattern in the surface layer of a northern California upwelling system," *J. Geophys. Res.* **95** (10), 18,081-18,094 (1990).